Physics Letters A 381 (2017) 1055–1066

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Tunability of band structures in a two-dimensional magnetostrictive phononic crystal plate with stress and magnetic loadings

Shunzu Zhang [a,b], Yang Shi [a,b], Yuanwen Gao [a,b,*]

[a] Key Laboratory of Mechanics on Disaster and Environment in Western China attached to the Ministry of Education of China, Lanzhou University, Lanzhou, Gansu 730000, PR China

[b] Department of Mechanics and Engineering Sciences, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou, Gansu 730000, PR China

ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 8 December 2016
Accepted 12 January 2017
Available online 31 January 2017
Communicated by M. Wu

Keywords:
Phononic crystal plate
Band gap
Magnetostrictive material
Magnetic field
Pre-stress

ABSTRACT

Considering the magneto-mechanical coupling of magnetostrictive material, the tunability of in-plane wave propagation in two-dimensional Terfenol-D/epoxy phononic crystal (PC) plate is investigated theoretically by the plane wave expansion method. Two Schemes, i.e. magnetic field is rotated in x–y plane and x–z plane, are studied, respectively. The effects of amplitude and direction of magnetic field, pre-stress and geometric parameters are discussed. For Scheme-I, band gap reaches the maximum at an optimal angle 45° of magnetic field. However, the optimal angle is 0° for Scheme-II, because band gap decreases monotonically until disappears with the increasing angle. For both cases, higher-order band gaps generate and become stronger as magnetic field amplitude increases, while increasing compressive pre-stress has the opposite effect. Meanwhile, filling fraction plays a key role in controlling band gaps. These results provide possibility for intelligent regulation and optimal design of PC plates.

1. Introduction

Phononic crystal (PC), referring to composite structure consisting of periodic arrays of acoustic or elastic inclusion in matrix system, has already attracted extensive attention from researchers. Based on the band gap characteristic that sound wave cannot propagate in some frequency ranges, PC has potential applications in the design of acoustic filters, waveguides, vibration isolators and noise suppressors [1–5]. Besides band gap characteristics of bulk wave propagation in two-dimensional (2D) infinite PC and wave localized at the surface of a semi-infinite 2D PC [6–8], the increasing attention of physics and engineering communities has been paid to the tunability of wave propagation behavior in finite thickness PC plates. Two types of PC plate structures [9–14]: periodic inclusions in a slab and periodic distribution of studs or gratings on the surface of plate have been reported in detail both theoretically and experimentally. These results show that the width and location of band gap are determined by the difference in elastic constants of inclusion and matrix, filling fraction, and lattice structure. Nevertheless, most of previous researches to date are focused on PC plate consisting of purely elastic materials.

Recently, the rise of intelligent materials gives new ideas to control PC band gap. A lot of efforts have been made to design intelligent phononic crystals whose band gap can be tuned by adjusting the geometry or physical parameters of constituent materials through external stimuli [15–30]. Zou et al. [18] demonstrated tunable wave propagation behavior by altering the polarized direction of piezoelectric material, and switching shunting circuit connected with piezoelectric patches in PC can trigger remarkable variation in band gap properties [19,20]. Feng and Liu [21] found band gap moves to a higher frequency region by an applied initial compressive stress. Wang et al. [22,23] studied the influence of piezoelectricity and piezomagneticity effects on band gap of magneto-electro-elastic phononic crystals. Bayat and Gordaninejad [24,25] revealed that the external magnetic field can control the elastic wave band structure of phononic crystal with soft magnetorheological elastomer. Since the elastic characteristic of magnetostrictive material is very sensitive to its magnetic state and extrinsic motivation, Matar et al. [26,27] considered the tunability of wave propagation behavior in 2D infinite PC with magnetostrictive material by applied magnetic field.

Considering the nonlinear magneto-mechanical coupling behavior of magnetostrictive material, some significant changes in band gap are analyzed. Ding et al. [28] researched the longitudinal wave propagation in epoxy/Terfenol-D and Ni6/Terfenol-D rod phononic crystals based on the magnetic and mechanical coupling interactions. Zhang et al. [29] further investigated the influence of tem-

---

[*] Corresponding author at: Key Laboratory of Mechanics on Disaster and Environment in Western China attached to the Ministry of Education of China, Lanzhou University, Lanzhou, Gansu 730000, PR China.

E-mail address: ywgao@lzu.edu.cn (Y. Gao).

http://dx.doi.org/10.1016/j.physleta.2017.01.044

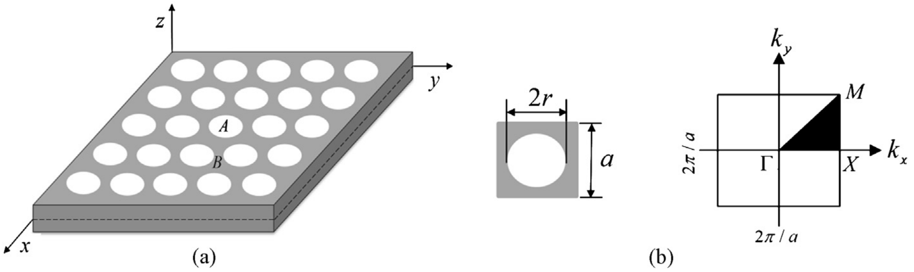

Fig. 1. (a) Schematic of a 2D phononic crystal thin plate with square lattice. (b) Diagram of square lattice unit cell and the first irreducible Brillouin zone (triangular area).

perature effect on band structure of epoxy/Terfenol-D rod phononic crystals. Lately, Gu and Jin [30] explored the dependence of point defect modes in 2D phononic crystal consisted of Terfenol-D rods embedded in a polymethyl methacrylate matrix on magnetic field and pre-stress applied in z direction. Numerical results demonstrated that new point defect modes are captured in band gap by applied suitable magnetic field and pre-stress. In these works, magnetic field is usually applied along a specific direction to optimize wave propagation behavior in PC. In fact, the directions of applied magnetic field and pre-stress are always complicated and changing in actual environment. Therefore, for PC composites including magnetostrictive material, the modulation of wave propagation behavior becomes more complex and more attractive, by not only the amplitude and orientation of magnetic field but also the pre-stress with different directions. Meanwhile, there may be an optimal direction of magnetic field corresponding to the best performance of band structure rather than the appointed direction in previous works. Thus, the study of the dependence of band structure on the magnetic and mechanical loading interactions with different directions becomes significant and necessary for PC structures. However, to our knowledge, few works have been reported in open literature studying on wave propagation in 2D magnetostrictive PC plate. So we focus on the effects of the amplitude and orientation of magnetic field, as well as pre-stress, further propose a theoretical model to give a better theoretical guidance to adjust and optimize wave propagation behavior in magneto-mechanical PC plate.

In this paper, based on the classical theory of in-plane wave in PC thin plate with the magnetostrictive material, ways for intelligent controlling of in-plane wave propagation in magneto-mechanical PC plate is studied by applied direction-dependent magnetic field and pre-stress. Taking two Schemes of applied magnetic field into account, a theoretical model is established to analyze the influence of magnetic and stress fields on the band structure characteristics of Terfenol-D/epoxy PC thin plate by the plane wave expansion (PWE) method. The numerical results show that an optimal angle can be found theoretically and drive band gap performance to the best, which is dependent on the different loading modes of magnetic field. Meanwhile, the amplitude and direction of magnetic field, pre-stress and geometric parameters should be considered simultaneously to better regulate band gap properties of PC thin plate operated in complicated engineering environment. The paper is organized into four sections, including the introduction above. A nonlinear magneto-mechanical theoretical model of PC thin plate used in the subsequent calculations is presented in section 2. Numerical results and discussion about the characteristics of band gaps are given in section 3. Finally, conclusions are drawn in section 4.

2. Theoretical model

The schematic diagram of a 2D phononic crystal thin plate with square lattice and the corresponding Cartesian coordinate system (o–xyz) are shown in Fig. 1(a), with the x–y plane locating at the mid-plane of the plate and the z axis along the thickness direction. We choose Terfenol-D as the inclusion and the epoxy as the matrix in PC plate, whose regions are denoted by A and B, respectively. The magnetostrictive material Terfenol-D is chose because it is widely used for actuators and intelligent devices due to its complex nonlinear magneto-mechanical coupling characteristics and sensitivity to external magnetic and mechanical stimuli [31–33]. Fig. 1(b) shows the unit cell and the first irreducible Brillouin zone (the triangular area Γ–X–M) of square lattice. In the unit cell, the radius of inclusion is r and the lattice constant is a. $\mathbf{k} = k_x\mathbf{i} + k_y\mathbf{j}$ is the Bloch wave vector. A perfect elastic coupling interfacial condition is assumed at the interface between two materials. It is assumed the thickness of plate h is much smaller than the lattice constant a in order to meet the condition of thin plate, thus the in-plane displacements can be expanding about the mid-plane values as $\overline{u_x}(x, y, z) \approx u_x(x, y)$, $\overline{u_y}(x, y, z) \approx u_y(x, y)$ [34]. For the 2D magneto-elastic PC thin plate, propagation of in-plane wave can be tuned by applying pre-stress and magnetic field loadings.

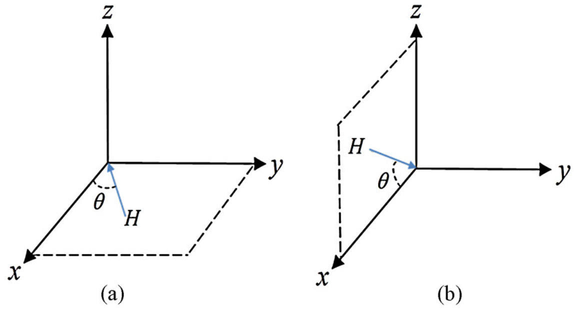

Fig. 2. Diagram of magnetic field loading modes (a) Scheme-I and (b) Scheme-II.

According to different loading modes of magnetic field direction, here, two Schemes are set as shown in Fig. 2 to design adjustable field-orientation PC thin plate with magnetostrictive material. As illustrated in Fig. 2, θ is the angle between the direction of applied magnetic field and the x axis. For Scheme-I and Scheme-II shown in Fig. 2(a) and Fig. 2(b), respectively, H can be applied in arbitrary direction within the x–y and x–z planes. Since the most possible in-plane residual stress state in the magnetostrictive film is equi-biaxial stress state, the biaxial pre-stress is usually assumed as $\sigma_x = \sigma_y = \sigma$ [31]. In addition, it is difficult to determine the value of initial shear stress accurately in current experimental techniques, so shear pre-stress is ignored in this paper. For the sake of brevity, the biaxial pre-stress is referred to as the “pre-stress”.

Taking demagnetization effect into account, the effective magnetic field can be calculated by [32]

$$\begin{cases} H_x = H\cos(\theta) - N_x M_x \\ H_y = H\sin(\theta) - N_y M_y \end{cases}, \tag{1}$$

for Scheme-I, and

$$\begin{cases} H_x = H\cos(\theta) - N_x M_x \\ H_z = H\sin(\theta) - N_z M_z \end{cases}, \tag{2}$$